What is quantum field theory and why have some physicists abandoned it?

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Abstract

The present-day crisis in quantum field theory is described.

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Quantum field theory offers physicists a tremendously wide variety of applications: it is both a language with which many physical processes can be discussed, and also it provides a model for fundamental physics, the so-called "standard model," which thus far has passed every experimental test. No other framework exists in which one can calculate so many phenomena with such ease and accuracy.

Arising from a mathematical account of the propagation of fluids (both "ponderable" and "imponderable"), field theory emerged over a hundred years ago in the description within classical physics of electromagnetism and soon thereafter of gravity. Schrödinger's wave mechanics became a bridge between classical and quantum field theory: the quantum mechanical wave function is also a local field, which when "second" quantized gave rise to a true quantum field theory, albeit a nonrelativistic one. Quantization of electromagnetic waves produced the first relativistic quantum field theory, which when supplemented by the quantized Dirac field gave us quantum electrodynamics, whose further generalization to matrices of fields is the present-day standard model of elementary particles. This development carries with it an extrapolation over enormous scales: initial applications were at microscopic distances or at energies of a few electron volts, while contemporary studies of elementary particles involve 10^{11} electron volts or short distances of 10^{-16} cm. The "quantization" procedure, which extended classical field theory's range of validity, consists of expanding a classical field in normal modes, and taking each mode to be a quantal oscillator.

Field theoretic ideas also reach for the cosmos through the development of the "inflationary scenario" — a speculative, but completely physical analysis of the early universe, which appears to be consistent with available observations. Additionally, quantum field theories provide effective descriptions of many-body, condensed matter physics. Here the excitations are not elementary particles and fundamental interactions are not probed, but the collective phenomena that are described by many-body field theory exhibit many interesting effects, which in turn have been recognized as important for elementary particle theory. Such exchanges of ideas between different subfields of physics demonstrate vividly the vitality and flexibility of field theory.

But in spite of these successes, today there is little confidence that field theory will advance our understanding of Nature at its fundamental workings, beyond what has been achieved. While in principle all observed phenomena can be explained by present-day field theory (in terms of the quantal standard model for particle physics and the classical Newton–Einstein model for gravity), these accounts are still imperfect. The particle physics model requires a list of *ad hoc* inputs that give rise to conceptual, general questions such as: Why is the dimensionality of space-time four? Why are there two types of elementary particles (bosons and fermions)? What determines the number of species of these particles? The standard model also leaves us with specific technical questions: What fixes the matrix structure, various mass parameters, mixing angles, and coupling strengths that must be specified for concrete prediction? Moreover, classical gravity theory has not been integrated into the quantum field description of nongravitational forces, again because of conceptual and

technical obstacles: quantum theory makes use of a fixed space-time, so it is unclear how to quantize classical gravity, which allows space-time to fluctuate; even if this is ignored, quantizing the metric tensor of Einstein's theory produces a quantum field theory beset by infinities that cannot be controlled.

But these shortcomings are actually symptoms of a deeper lack of understanding that has to do with symmetry and symmetry breaking. Physicists mostly agree that ultimate laws of Nature enjoy a high degree of symmetry, that is, the formulation of these laws is unchanged when various transformations are performed. Presence of symmetry implies absence of complicated and irrelevant structure, and our conviction that this is fundamentally true reflects an ancient aesthetic principle: physicists are happy in the belief that Nature in its fundamental workings is essentially simple. However, we must also recognize that actual, observed physical phenomena rarely exhibit overwhelming regularity. Therefore, at the very same time that we construct a physical theory with intrinsic symmetry, we must find a way to break the symmetry in physical consequences of the model.

Progress in physics can frequently be seen as the resolution of this tension. In classical physics, the principal mechanism for symmetry breaking is through boundary and initial conditions on dynamical equations of motion. For example, Newton's rotationally symmetric gravitational equations admit the rotationally nonsymmetric solutions that describe actual orbits in the solar system, when appropriate, rotationally nonsymmetric, initial conditions are posited.

The construction of physically successful quantum field theories makes use of symmetry for yet another reason. Quantum field theory models are notoriously difficult to solve and also explicit calculations are beset by infinities. Thus far we have been able to overcome these two obstacles only when the models possess a high degree of symmetry, which allows unraveling the complicated dynamics and taming the infinities by renormalization. Our present-day model for quarks, leptons, and their interactions exemplifies this by enjoying a variety of chiral, scale/conformal, and gauge symmetries. But to agree with experiment, most of these symmetries must be absent in the solutions. At present we have available two mechanisms for achieving this necessary result. One is *spontaneous symmetry breaking*, which relies on energy differences between symmetric and asymmetric solutions: the dynamics may be such that the asymmetric solution has lower energy than the symmetric one, therefore the former is realized in Nature while the latter is unstable. The second is *anomalous* or *quantum mechanical symmetry breaking*, which uses the infinities of quantum theory to effect a violation of the correspondence principle: the symmetries that appear in the model *before* quantization disappear *after* quantization, because the renormalization procedure — needed to tame the infinities and well define the theory — cannot be carried out in a fashion that preserves the symmetries.

While these two methods of symmetry breaking successfully reduce the symmetries of the standard model to a phenomenologically acceptable level, this reduction is achieved in an *ad hoc* manner, and much of the previously mentioned arbitrariness,

which must be fixed for physical prediction, arises precisely because of the uncertainties in the symmetry-breaking mechanisms. Spontaneous symmetry breaking is adopted from many-body, condensed matter physics, where it is well understood: the dynamical basis for the instability of symmetric configurations can be derived from first principles. In the particle physics application, we have not found the dynamical reason for the instability. Rather, we have postulated that additional fields exist, which are destabilizing and accomplish the symmetry breaking. But this *ad hoc* extension introduces additional, *a priori* unknown parameters and yet-unseen particles, the Higgs mesons. Anomalous symmetry breaking also carries with it arbitrariness: the QCD "renormalization scale" as well as yet-unseen particles, the axions, which fix an arbitrary CP-violating angle. Moreover, the field theoretic infinities, which give rise to anomalous symmetry breaking, prevent the construction of an acceptable quantum gravity field theory, so it is peculiar to rely on them so critically for the viability of the standard model.

Advancing our understanding of the above has been at an impasse for over two decades. In the absence of new experiments to channel theoretical speculation, some physicists have concluded that it will not be possible to make progress on these questions within field theory, and have turned to a new structure, *string theory*. In field theory the quantized excitations are point particles with point interactions and this gives rise to the infinities. In string theory, the excitations are extended objects — strings — with nonlocal interactions; there are no infinities, and this enormous defect of field theory is absent. Not only does quantum gravity exist in the new context, but it appears that some puzzles having to do with black holes can be answered. Moreover, string theory addresses precisely some of the questions that remained unanswered in field theory: dimensionality of space-time cannot be arbitrary because string theory cannot be formulated in arbitrary dimensions; fermions must coexist with bosons because of supersymmetry — a necessary ingredient of string theory; and so on.

Yet in spite of these positive features, up to now string theory provides only a framework, rather than a definite structure. While present-day physics should be found in the low-energy limit of string theory, a precise derivation of the standard model has yet to be given. One thinks again about symmetry and symmetry breaking. The symmetries of quantum field theory surpass those of classical physics and require elaborate symmetry breaking mechanisms. The symmetries of string theory again vastly outpace those of field theory, and must be broken by yet-to-be-developed procedures, in order to explain the world around us.

On previous occasions when it appeared that quantum field theory was incapable of advancing our understanding of fundamental physics, new approaches and new ideas dispelled the pessimism. Today we do not know whether our lack of progress is due to a failure of imagination, or whether indeed we have to present fundamental physical laws in a new framework, thereby replacing the field theoretic one, which has served us well for over a hundred years.